PCMDI

Program for Climate Model Diagnosis and Intercomparison

PCMDI Report No. 11

PRELIMINARY VALIDATION OF THE LOW FREQUENCY VARIABILITY OF TROPOSPHERIC TEMPERATURE AND CIRCULATION SIMULATED FOR THE AMIP BY THE ECMWF MODEL

by

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April 1993

ABSTRACT

The ECMWF global model (cycle 36) is used to simulate the climate from 1979 to 1988. This integration is in support of the WGNE Atmospheric Model Intercomparison Project (AMIP). The model uses the observed monthly sea surface temperature for the ten year period during the integration. Anomaly correlation and RMS calculations are carried out between monthly mean observed circulation (ECMWF analyses and MSU channel 2 temperatures) and the model results, although the use of monthly mean data restricts the conclusions to the low frequency variability. The variables and regions considered are the 500 hPa geopotential and MSU temperatures for the Northern Hemisphere (30N to 70N), the 200 hPa zonal wind and MSU temperatures for the equatorial belt (15S to 15N), and the 1000 hPa zonal wind for the equatorial Pacific (15N to 15S and 120E to 100W).

The results show: (1) For the midlatitude 500 hPa geopotential there is a signal in the model results for the ENSO events of 1982/83 and 1986/87; (2) the model underestimates the midlatitude 500 hPa geopotential interannual variability as measured by the RMS but overestimates the MSU temperature variability in this region; (3) in general, outside of the ENSO periods, there is little correlation between the model and observed data anomalies of midlatitude 500 hPa geopotential; (4) in the tropics the variables evince a stronger correlation with observations, with the 200 hPa winds yielding greater agreement than the MSU temperatures and the 1000 hPa zonal wind showing a significant correlation with observations in the interannual variation; (5) in the tropics the model underestimates the variability of the 200 hPa wind and MSU temperature; (6) the model, although non-interacting with the ocean, produces a credible simulation of the low frequency variability of the equatorial JPacific low level zonal wind.

1. Introduction

The nature of the ocean forcing on the low frequency atmospheric behavior is at present not completely understood. From the extensive study of ENSO events there is copious documentation, (e. g. Philander, 1990), as to the fact of their mutual interaction but many details remain to be elucidated. In this paper an experiment is described which addresses a small part of the ocean forcing issue. The experiment is to run a comprehensive atmospheric GCM for a decade with observed sea surface temperatures (SST) and sea ice specified. The simulation was one of those done as part of the AMIP (Gates, 1992). The land surface temperatures are allowed to vary in accord with the model's surface energy balance. The expectation is that any interannual variation, aside from the intrinsic non-deterministic variability, would be largely determined by the SST variations. The period 1980 to 1988 was chosen because there were verifying analyses available. Monthly means are chosen for the model evaluation in order to focus on the low frequency variability. Wallace and Blackmon (1983) show that monthly mean fields closely resemble low pass filtered fields of a period greater than about ten days. If the response of the model to the SST forcing is similar to that of the real atmosphere and the atmospheric response has a low frequency component strongly influenced by the SST pattern, then the model data presented here should have an interannual variation resembling that found in observations.

As is obvious, there are places where the linkage between the model results and observations can break down. First, the model may not correspond to reality. This is certainly true in an absolute sense, but is the model adequate to capture the essential processes that make up the interaction? Second, the SST signal may not be the dominant effect in the atmosphere of the model. Because the only link between the model simulation and the observations is the SST, if the SST explains only a small part of the variance, the two data sets might have little relation to each other. Finally, the SST signal in the real atmosphere may be very small, so that a properly behaving model would most likely not exhibit a close relation to the observations and the intrinsic variability would swamp the signal detectable by the simple methods used here.

In this paper a preliminary evaluation of the model against observations will be attempted. The evaluation tests are the anomaly correlation, and the root-mean square error and correlation coefficient of the anomalies. The verification data are analyses of wind and geopotential from ECMWF analyses and mean tropospheric

temperatures produced from the MSU observations. In the next section the model will be briefly described and the details of the integration explained. Subsequent sections describe the verifying analyses and the results of the evaluation.

2. Model

The model which is used for this experiment is the ECMWF operational model, cycle 36. The model has 19 levels in the vertical and for this experiment was set to a horizontal resolution of T42. The model is in all respects the same as that described by Miller et al. (1992). The resolution is a compromise between the conflicting demands of sufficient resolution and realistic computation time. The work of Tibaldi et al. (1991) indicates that the T42 resolution is adequate for the type of study performed here. The sea surface temperatures are the observed monthly average values as specified for AMIP (Gates, 1992). The surface land temperatures are allowed to vary freely in accordance to the surface parameterizations. The integration was started with the ECMWF analysis for 1 January 1979 and proceeded for 10 years. The verifying analyses were not available for the first year (1979).

3. Observational data set

The observational data available are the operational analyses of ECMWF. The data are on a 2.5 x 2.5 degree grid on standard pressure levels and are in the form of monthly means. There are well-documented problems with the ECMWF data set as regards the changing analysis and assimilation system over the period considered here (Hoskins et al., 1989). The two most prominent changes occurred in September 1982 when the ECMWF data assimilation cycle began using diabatic initialization, and in May 1985 when the T106 model was introduced, which represented a significant increase in resolution and upgrade in the physics. The diabatic initialization had a significant impact on the analysis of the divergent component of the circulation in the tropics. Despite these changes, these data represent the best global data presently available.

The temperatures obtained from the Microwave Sounding Unit (MSU), which is carried on the NOAA polar orbiting satellites, provide a verification data set that is independent of the ECMWF data are. These data are described by Spencer and Christy (1990). The channel 2 values provide global measures of a weighted vertical mean of the tropospheric temperature. Using the weighting function shown in Spencer and Christy (1990), the pressure level data from the model and the ECMWF analyses can be transformed into values corresponding to the MSU data as described by Hurrell and Trenberth (1992). The ECMWF analyses that were used extended only to 100 mb.

4. Computations

The equations for the anomaly correlation (AC) and the correlation coefficients of the anomaly (CCA) are as follows:

$$AC = \frac{\langle \Delta x \Delta x_a \rangle}{\sqrt{\langle \Delta x^2 \rangle \langle \Delta x_a^2 \rangle}} \tag{1}$$

$$CCA = \frac{\langle \delta x \delta x_a \rangle}{\sqrt{\langle \delta x^2 \rangle \langle \delta x_a^2 \rangle}} \tag{2}$$

$$
\begin{aligned}
\langle x \rangle &= \text{area average} \\
\delta x &= x - x_c \\
\delta x_a &= x_a - x_c \\
\Delta x &= \delta x - \langle \delta x \rangle
\end{aligned}
\tag{3}
$$

where: x_a = analysis(observations), x_c = climatology(time mean of x_a)

The climatology used in computing the anomaly correlation was the nine year average for the appropriate data set. These measures have been used in many efforts to evaluate the results of GCM simulation.

5. Selected regional analysis

The nature of the atmospheric response suggests that the midlatitudes and tropics should be discussed separately. The observational data available in the Northern

Hemisphere are much greater than those in the Southern Hemisphere, so we will exclusively consider the northern midlatitudes for verification. The tropics present a problem as far as verification data are concerned, and it is here that the MSU data are useful. In the midlatitudes the 500 hPa geopotential is chosen for verification. This choice is made since there is a long history of verification using this variable, the accuracy of the analyses for 500 hPa is good and the geopotential provides a useful dynamical and thermodynamical measure in midlatitudes. In the tropics the 200 hPa winds are used for verification. The accuracy of the upper level tropical wind analyses are open to debate but are probably adequate for the present use.

a. *Northern Hemisphere (30N to 70N)*

Figure 1 shows the AC between the model and observed (ECMWF) 500 hPa geopotential for the Northern Hemisphere from 30N to 70N for the years 1980 to 1988.
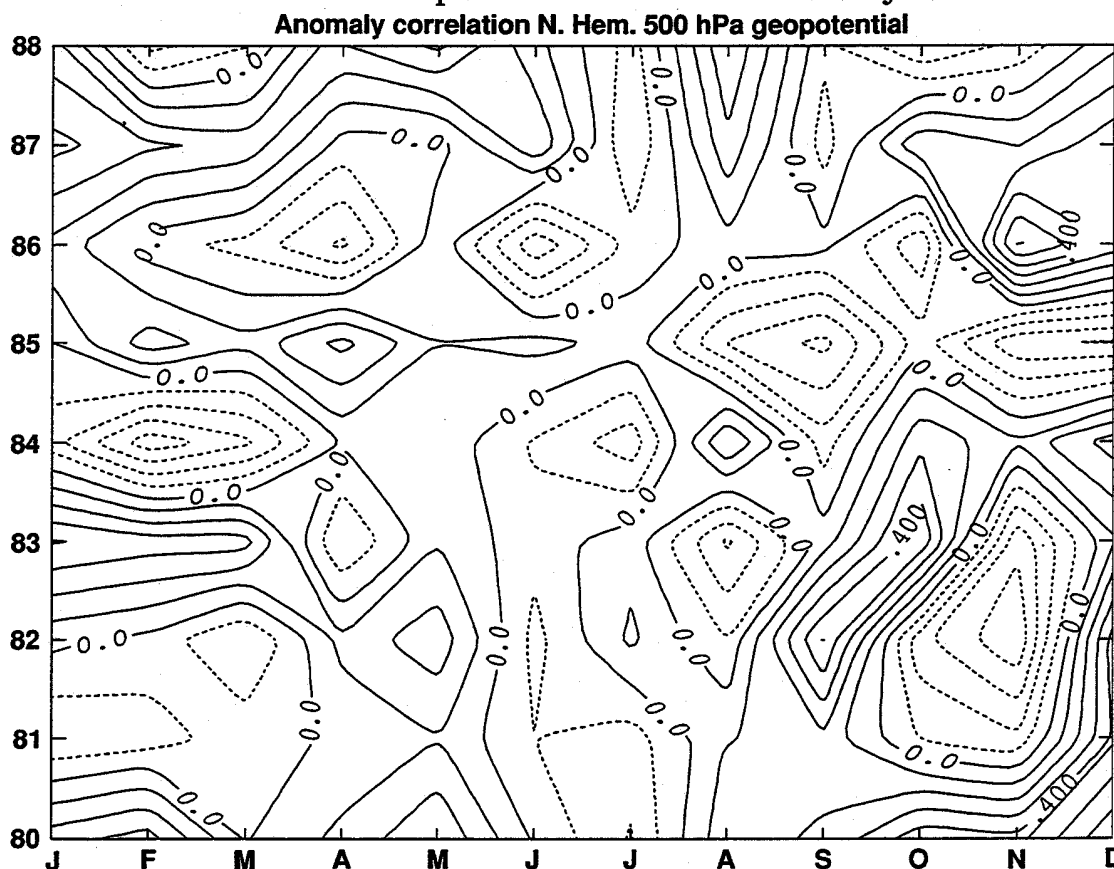

Fig. 1. Anomaly correlation between monthly mean ECMWF analyses and model simulated 500 hPa geopotential from 30N to 70N for years 1980 to 1988 (ordinate) from January to December (abscissa). Contour interval is 0.1. Solid lines indicate positive values, dashed lines indicate negative values.

The plot is quite noisy with little apparent structure. The largest values, positive and negative, tend to be in the winter, but other than that there is no dominant systematic variation. Likewise, there is little evidence for sustained high (or low) correlations in a given year or season. As Wallace and Blackmon (1983) point out, there are possible forcings other than SST in midlatitudes and in general the SST midlatitude signal is weak. There are, however, two interesting periods in this figure. The first is December 1982 to March 1983 and, the second is from November 1986 to March 1987. Both of these periods correspond to ENSO events where the SST anomaly was strong and where one might expect the SST signal into midlatitudes, if it exists, to be strongest. The maxima in the AC pattern for these periods suggest that the model is responding to the SST patterns in a realistic fashion.

Figure 2 shows the AC between the model and observed mean January 500 hPa geopotential from 1980 to 1988 for the Northern Hemisphere from 30N to 70N. The curve in Fig. 2 can be generated from the data for January in Fig. 1. The AC is small,
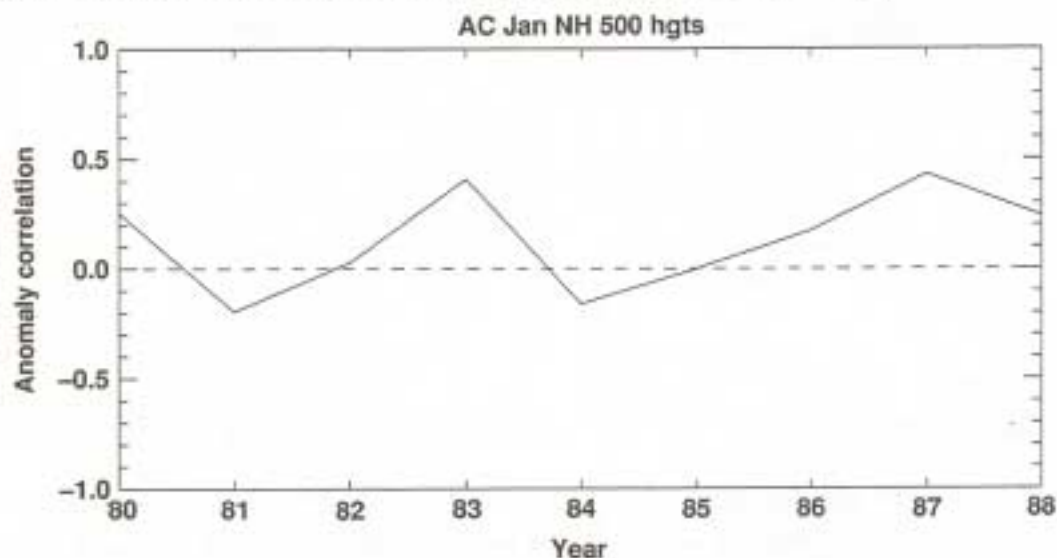

Fig. 2. Anomaly correlation between the monthly mean ECMWF analyses and model simulated 500 hPa geopotential from 30N to 70N for the Januarys of the years 1980 to 1988.

except for two prominent exceptions during the times mentioned above coincident with significant ENSO events. At these times the AC reaches (the still small) value of about 0.4. One might infer from this that the extratropical low frequency response to the tropical SST anomalies only becomes significant for the truly large SST events. On the other hand, it could indicate that the model response is insensitive to the SST

anomalies until they become overwhelming, and that the atmosphere actually responds in other years as well but that the model does not capture this interaction. Another possibility is that the model does capture the response but the signal is too small to be detected by this simple analysis.

Figure 3 shows the anomalies of the 500 hPa geopotential from observations and the model for January 1983 and January 1981. These two months represent the maximum and minimum in Fig. 2. As seen in Figs. 3a and 3b, the model captures the negative anomaly off western North America and the positive anomaly across eastern
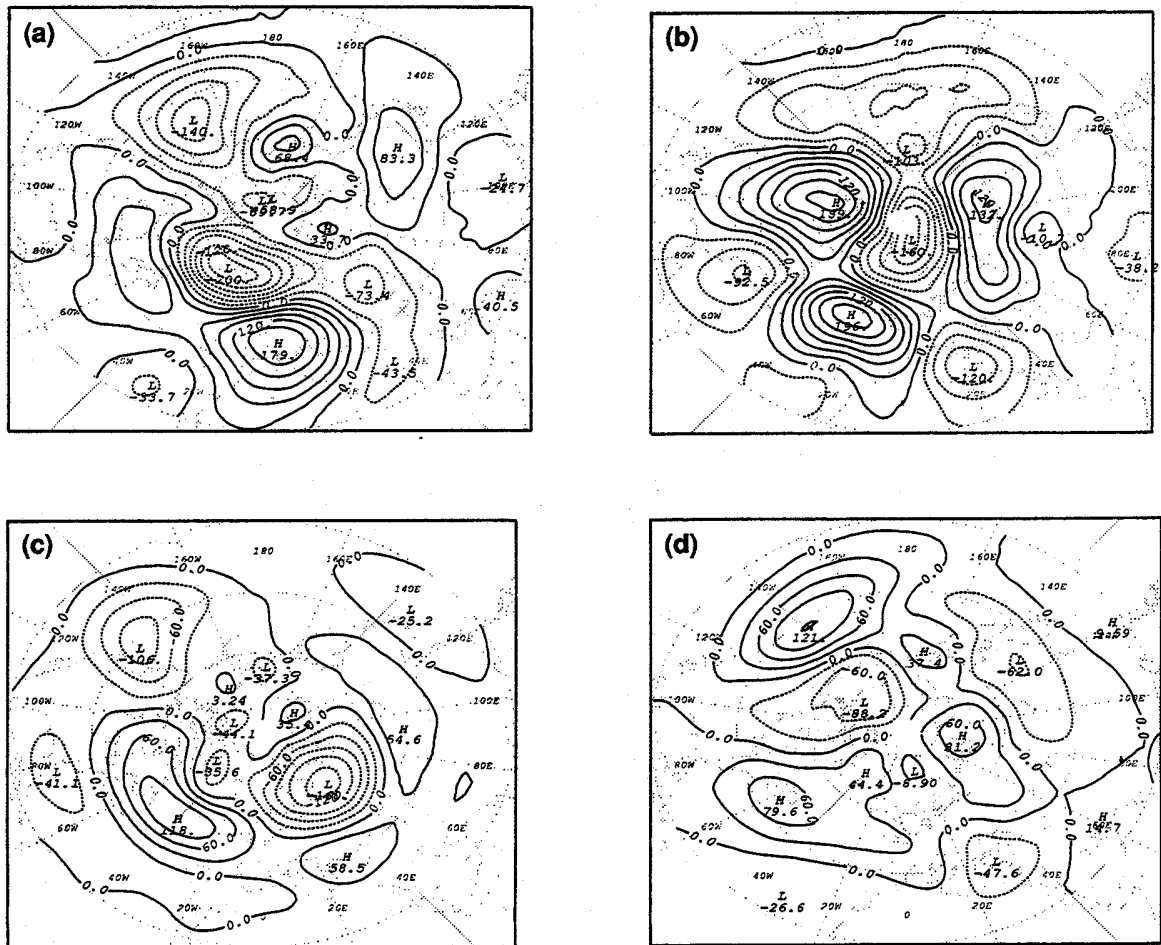

Fig. 3. (a) Anomalies of 500 hPa geopotential for the month of January 1983 for the observed ECMWF data. Contour interval in 30 geopotential meters. Solid lines indicate positive anomalies (individual monthly value greater than 9 year–mean for that month), dashed lines indicate negative values. (b) As in (a) except for the model data. (c) As in (a) except for January 1981 (d) As in (b) except for January 1981.

North America, although the model did quite poorly over the North Atlantic and Europe. The poor correspondence between the model and observation seen in Figs 3c and 3d illustrates the reason for the poor overall correlation. Note that the character of the anomalies in both months in the model is somewhat muted compared to the observed anomalies. The amount of variability in the model is less than that observed, as will become evident when the interannual variations are considered later.

Figure 4a is a time series of the AC for the 108 months from January 1980 to December 1988. The curve has many rapid fluctuations, with little evidence for a common signal forced by the relatively slowly varying SST. The periods of the ENSO events are detectable as more sustained periods of high AC. There are periods not related to ENSO events, as at the end of 1980, with comparable AC. The time series gives the impression of almost random fluctuations, which would be the case if the model (and atmospheric) variability is dominated by intrinsic or natural variability.
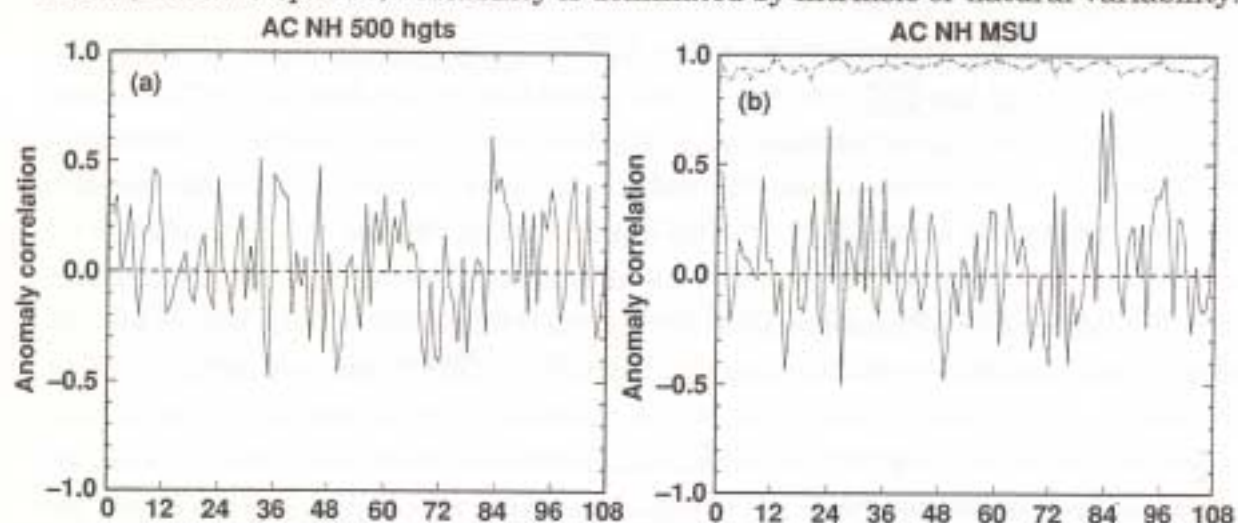

Fig. 4. (a) Time series of the anomaly correlation between the monthly mean ECMWF analyses and model simulated 500 hPa geopotential from 30N to 70N for the years 1980 to 1988 (108 months). The tick marks to the right of the year on the abscissa are the data points for December of that year. (b) As in (a) except for the MSU temperatures. The solid curve is the anomaly correlation between the MSU observations and the model simulation. The dash-dot line is the anomaly correlation between ECMWF analyses and the MSU observations.

Figure 4b is the same as Fig. 4a except for the MSU temperatures. In this case the observed MSU temperatures are the verification data so there are two curves: one for the model and the other for the ECMWF analyses. As can be seen the ECMWF

data agree quite well with the MSU data in terms of this measure. The modest peak at the end of 1982 and the beginning of 1983 in Fig. 4a is not seen in Fig. 4b. The linear correlation with the model curves of Fig. 4a and4b is 0.6. The lack of a peak in the MSU data corresponding to the peak in 1982–83 in Fig. 4a could be due to vertical compensation in the temperatures of the anomalies for this period.

It might be possible that the model is responding to the SST variations in a slightly different fashion than the atmosphere, such that the position of the anomalies is different. Hoerling et al. (1992) note a phase shift in the CCM1 streamfunction anomaly response to the 1985–86 ENSO event. The penalty in AC scores for a small variation in the phase of an anomaly is severe. Yet the model might be providing useful information on the interannual variability. One way of bringing this out is to compute the AC between years for a given month for both the observations and the model for all possible combinations of the nine years. The idea is that if the atmospheric low frequency variations are responding to the SST, this will produce a variation between the years driven by the SST variation. If the model also responds to the SSTs in a similar fashion, it may not reproduce the anomalies in the same position as the atmosphere but the different years should be like or unlike as reflected in the AC scores in the same way as the atmosphere. Figure 5 is an attempt to see if such a relation exists. Figure 5a shows the AC scores between all possible pairs of Northern Hemisphere, January 500 hPa geopotential (36 for the 9 Januarys) for the model and the observations plotted as a scatter diagram with the ECMWF analysis as the abscissa. The month of January is chosen since the anomalies of the circulation are usually largest in the wintertime. If the interannual variations were dominated by the SST pattern in both the atmosphere and the model and the model properly simulated the atmospheric response, one would expect the points to fall along the diagonal. The linear correlation coefficient is 0.05, which supports the hypothesis of no significant correlation.Evidently the SST do not have a significant role in the midlatitude low frequency variability and/or the model does not respond in the same fashion as does the atmosphere.

Figure 5b is the same as Fig. 5a except for the MSU temperatures. There are two sets of points since the model data, and the ECMWF analyses are both plotted against the MSU observations on the abscissa. The ECMWF and MSU data agree well with a linear correlation of 0.99. The model data has a linear correlation of -0.25 with the observations, indicating that, overall, this model bears little relation to the observations
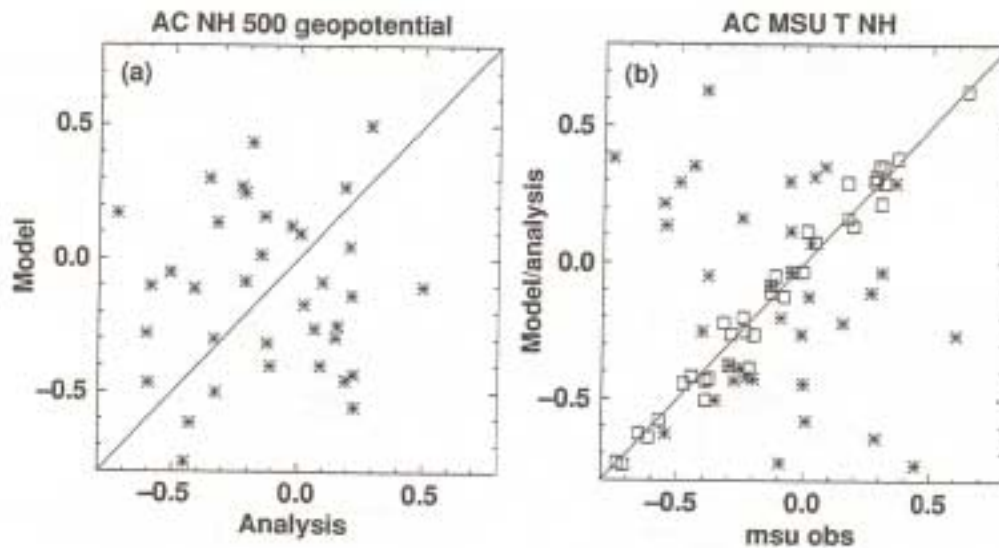
Fig. 5. (a) Anomaly correlation between all possible pairs of January monthly mean 500 hPa geo-potential from 30N to 70N for the years 1980 to 1988 plotted as a scatter diagram. The values for the ECMWF analyses are plotted along the abscissa, model values along the ordinate. For the nine Janu-arys there are 36 pairs. (b) As in (a) except for the MSU temperatures. The asterisks are the ECMWF analyses, the diamonds are the model simulation. The abscissa is the values of the MSU observations.

using this measure of interannual variation. These data give confidence to the accu-racy of the midlatitude ECMWF analyses in capturing the anomalies in temperature in the Northern Hemisphere.

Figure 6 is the same as Fig. 5 except for the RMS instead of AC. Figure 6a shows that the magnitude of the interannual variations of 500 hPa geopotential is in general larger in the observations than in the model. Points to the right of the diagonal indi-cate that the model values are smaller than the analyses. The figure implies that the model does need improvement in enhancing its variability of this key field. The lack of model variability was also noted in Fig. 3 where the anomalies of the individual modeled months were shown to have little structure.

The RMS data for the MSU temperatures, Fig. 6b, give different results. The model data indicate a greater variability on the part of the model as compared to ob-servations, and this variability must come from the model atmosphere above 500 hPa. The real atmosphere evidently compensates for the large variability below 500 hPa, a process not completely captured by the model.
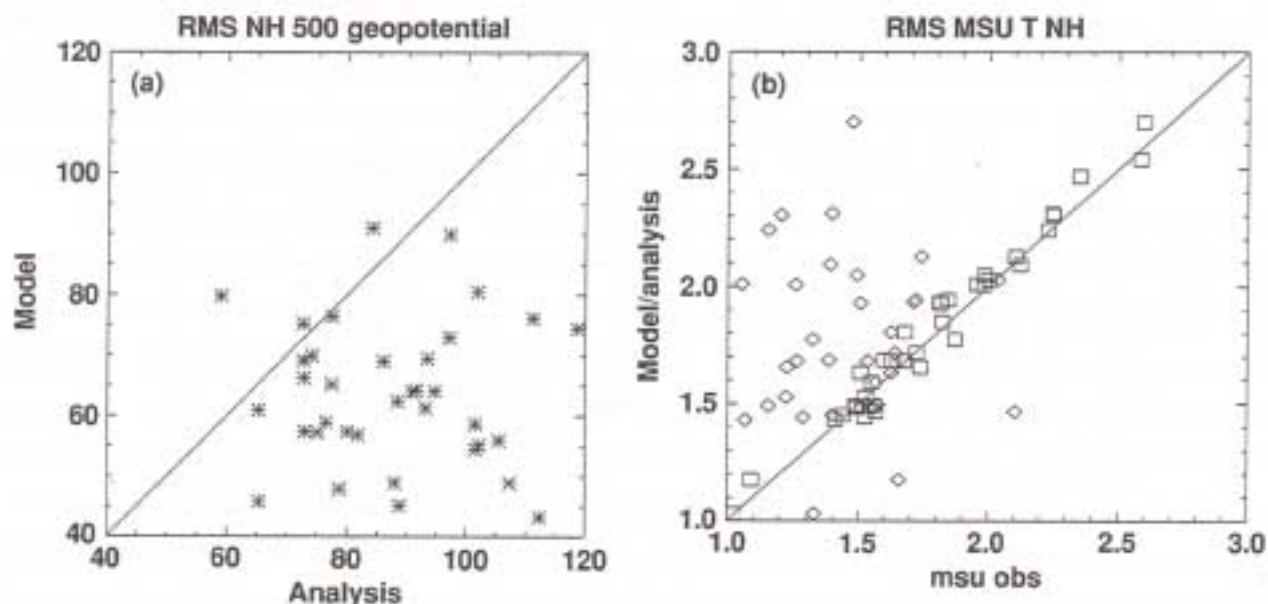
Fig. 6. (a) RMS between all possible pairs of January monthly mean 500 hPa geopotential from 30N to 70N for the years 1980 to 1988 plotted as a scatter diagram. The values for the ECMWF analyses are plotted along the abscissa, model values along the ordinate. For the nine Januarys there are 36 pairs. (b) As in (a) except for the MSU temperatures. The asterisks are the ECMWF analyses, the diamonds are the model simulation. The abscissa has the values of the MSU observations.

b. Tropics (15S to 15N)

Studies have shown that the equatorial regions are sensitive to variations in the SST, Philander, 1992. This is partly because of the dynamics of the tropical circulation and partly because the largest SST anomalies occur in the tropics. Figure 7 shows the AC between the model and the observed 200 hPa zonal wind for the region 15S to 15N for the same time periods as Fig. 1. This figure shows more coherent structure than Fig. 1, with periods of sustained correlation and anticorrelation. Newell and Xu (1992) note that the correlation between the atmospheric and ocean temperatures is somewhat more persistent in the tropics than in the midlatitudes. In their study periods of high correlation between ocean temperature and atmospheric temperature in midlatitudes were sustained for only a month or two. This same behavior in the model is evident comparing Figs. 1 and 7 (and is also true of the data in the next section). The 1982/1983 ENSO event stands out as a period of high AC. There are also periods (such as the last half of 1985) when the model in quite unlike the observations.
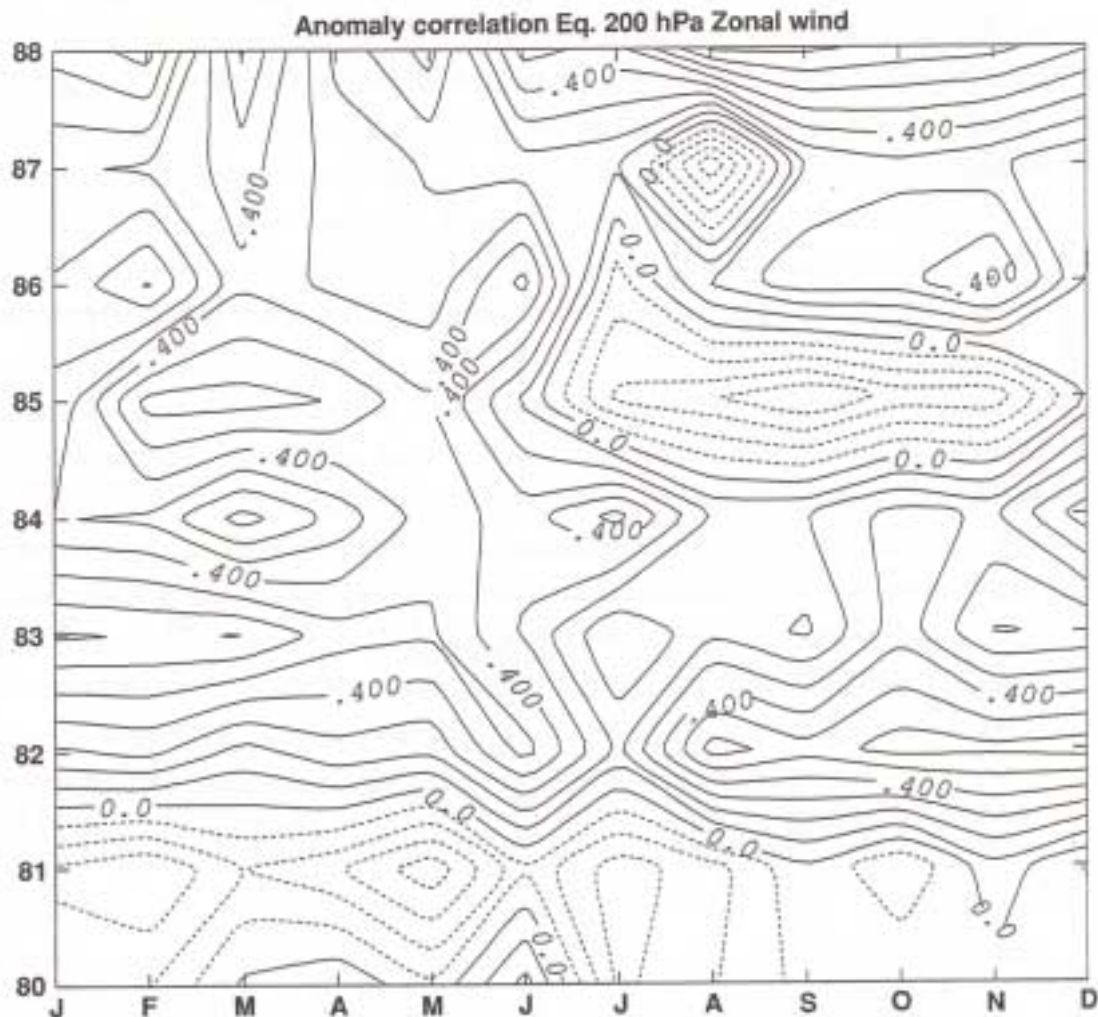
Fig. 7. Contours of anomaly correlation between the monthly mean ECMWF analyses and model simulated 200 hPa zonal wind from 15S to 15N for the years 1980 to 1988(ordinate) from January to December(abcissa). Contour interval is 0.1. Solid lines indicate positive values, dashed lines indicate negative values.

Figure 8a is the time series of the AC for Jan 1980 to Dec 1988 for the equatorial 200 hPa zonal wind. The 1982/83 ENSO event is evident as a period of high AC, while the 1986/87 event is somewhat less discernible. Figure 8b is the same as Fig. 8a except for the MSU temperatures. Compared to the northern hemisphere data the ECMWF analyses possess somewhat less agreement in the tropics. Overall, there is a good correspondence between the model and the ECMWF data, the linear correlation
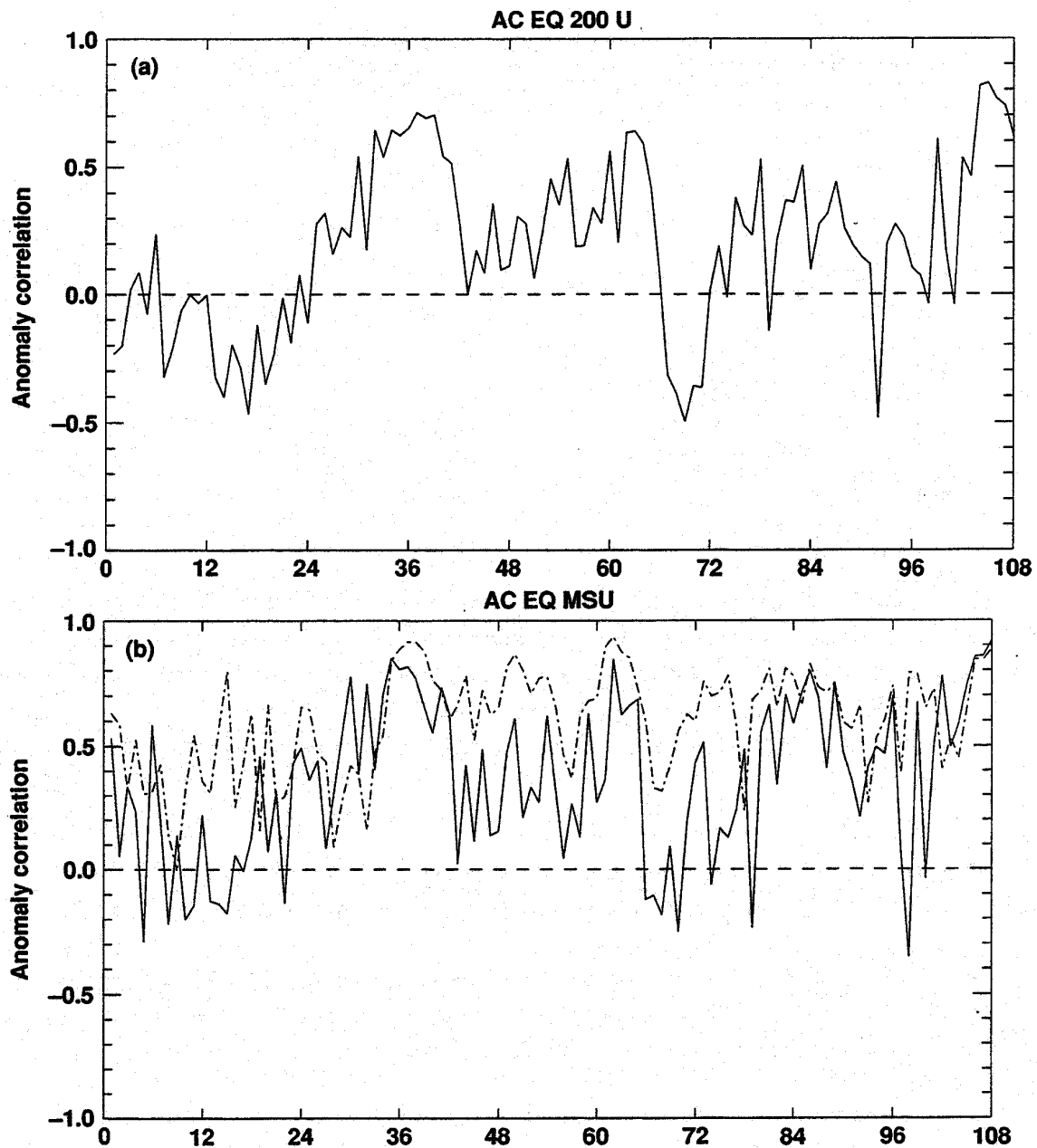
Fig. 8. (a) Time series of the anomaly correlation between the monthly mean ECMWF analyses and model simulated 200 hPa zonal wind from 15S to 15N for the years 1980 to 1988(108 months). The tick marks to the right of the year on the abscissa are the data points for December of that year. (b) As in (a) except for the MSU temperatures. The solid curve is for the anomaly correlation between the MSU observations and the model simulation. The dash-dot line is the anomaly correlation between ECWMF analyses and the MSU observations

coefficient being 0.92. This correspondence might be the result of the fact that in the absence of data the analyses will revert to the model first guess, and in this case the model is that of the ECMWF itself. Although the model used in the analysis has changed over the years, the model configurations are similar to the one used in the present simulation. Thus, in the tropics where the data are sparse, the analyses are much like the present model and evidently the operational model produces a similar response to the same SST pattern as does the model in the experiment. There are observed high AC values during ENSO periods but there are equally high AC values in other periods also.

Figure 9a is the same as Fig. 5a, except for the equatorial 200 hPa zonal wind. Here the interannual variations have a linear correlation coefficient of -0.06. For this variable, as for the 500 hPa midlatitude heights, the common link of the SST does not seem to be enough to drive the model and atmosphere in a similar fashion. Figure 9b is the same as Fig. 9a except for the MSU temperatures. The linear correlation between the observations and the ECMWF analyses is 0.7, indicating that the analyses capture most of the interannual variations. The model and the observations have a correlation of only 0.19, perhaps smaller than one might expect for a variable (i.e. the MSU temperature) that should be influenced by the SST.
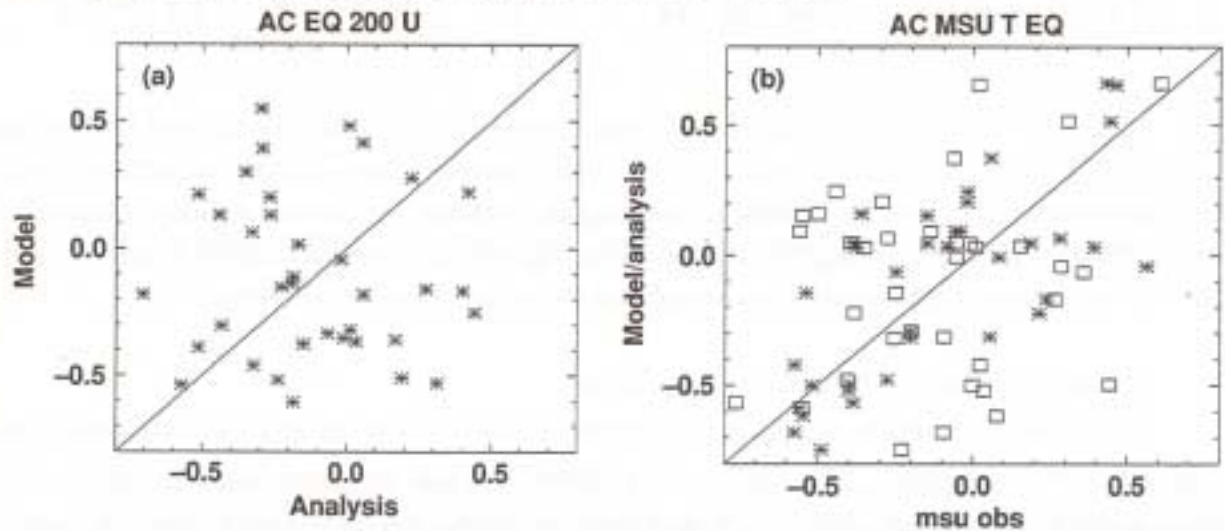

Fig. 9. (a) Anomaly correlation between all possible pairs of January monthly mean 200 hPa zonal wind from 15S to 15N for the years 1980 to 1988 plotted as a scatter diagram. The values for the ECMWF analyses are plotted along the abscissa, model values along the ordinate. For the nine Januarys there are 36 pairs. (b) As in (a) except for the MSU temperatures. The asterisks are the ECMWF analyses, the diamonds are the model simulation. The abscissa has values of the MSU observations.

Comparison of the two interannual RMS data in Fig. 10a indicates that the model underestimates the variability in the equatorial upper level winds as it did for the 500 hPa heights. Figure 10b shows the corresponding RMS data for the MSU temperatures. The linear correlation between the variations of RMS in the observations and the model is only 0.05. Here the model tends to underestimate the variability, while in midlatitudes it overestimated the variability. The ECMWF analyses show a rather pronounced tendency to seriously underestimate the interannual variations.
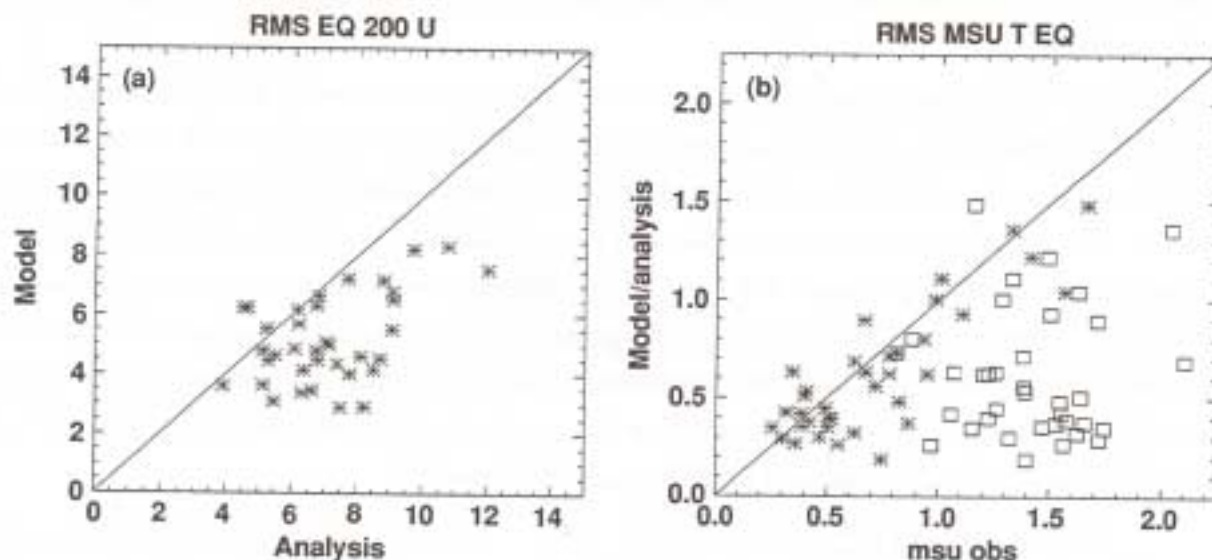

Fig. 10. (a) RMS between all possible pairs of January monthly mean 200 hPa zonal wind from 15S to 15N for the years 1980 to 1988 plotted as a scatter diagram. The values for the ECMWF analyses are plotted along the abscissa, model values along the ordinate. For the nine Januarys there are 36 pairs. (b) As in (a) except for the MSU temperatures. The asterisks are the ECMWF analyses, the diamonds are the model simulation. The abscissa has the values of the MSU observations.

c. *Equatorial Pacific 1000 hPa zonal wind*

There is obviously a signal in the ENSO time periods for the two variables and regions described above. To focus on the ENSO events, we next consider the region from 120E to 100W and 15S to 15N, and look at the AC and RMS of the 1000 hPa zonal wind. This variable is a prime constituent of an ENSO event and the equatorial Pacific is the location of the major signal of SST variability (Reynolds, 1988). However, the model atmosphere is not interacting with the ocean, thus the signal that is seen is the model's response to an imposed SST could be different from that of the fully
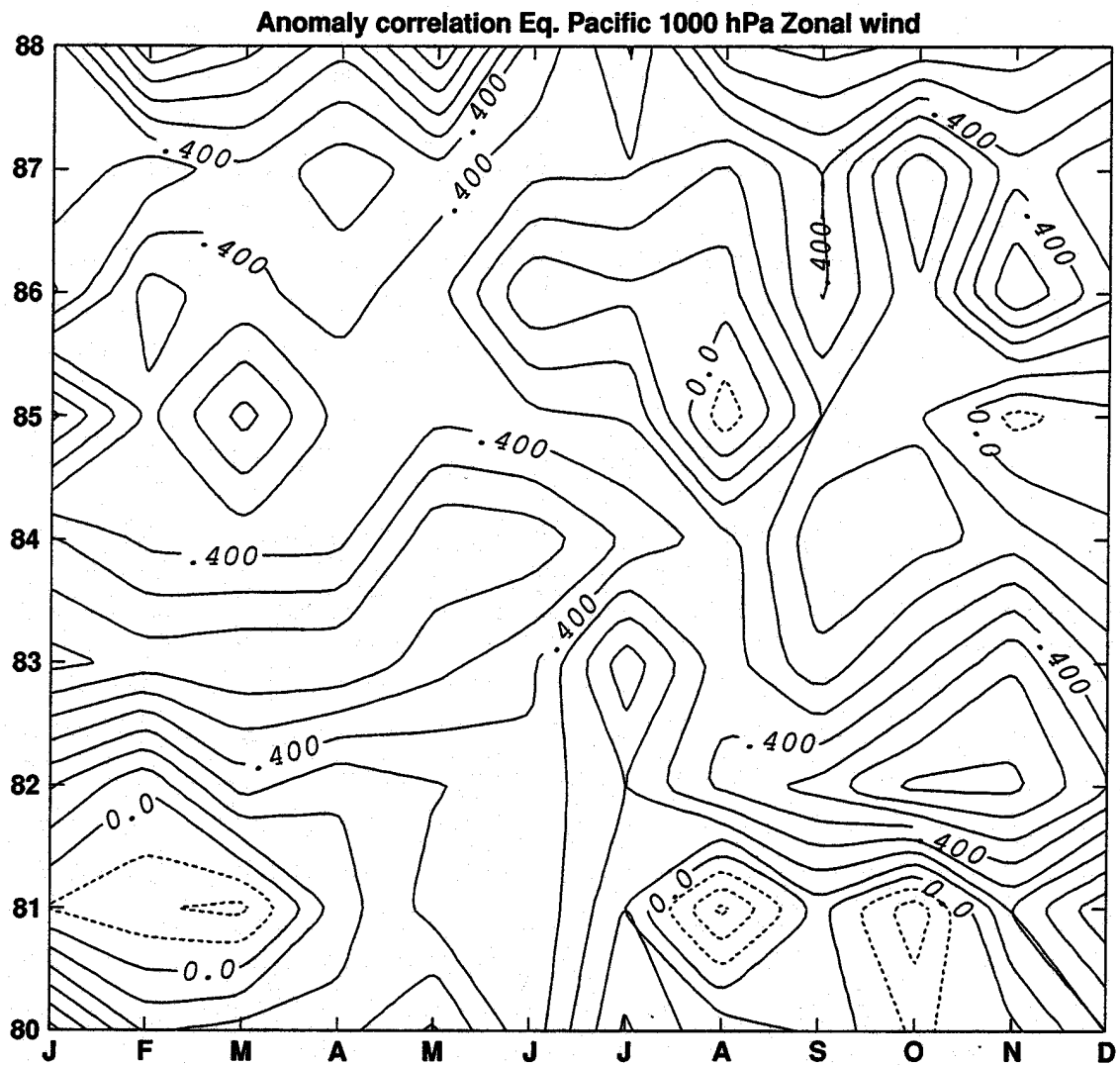
Fig. 11. Contours of anomaly correlation between the monthly mean ECMWF analyses and model simulated 1000 hPa zonal wind from 15S to 15N and 120E to 100W for the years 1980 to 1988(ordinate) from January to December(abcissa). Contour interval is 0.1. Solid lines indicate positive values, dashed lines indicate negative values.
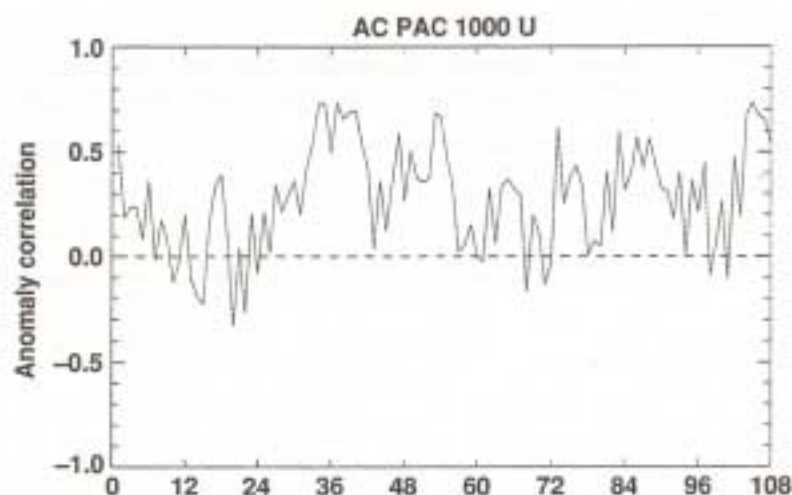
Fig. 12. Time series of the anomaly correlation between the monthly mean ECMWF analyses and model simulated 1000 hPa zonal wind from 15S to 15N and 120E to 100W for the years 1980 to 1988(108 months). The tick marks to the right of the year on the abscissa are the data points for December of that year.
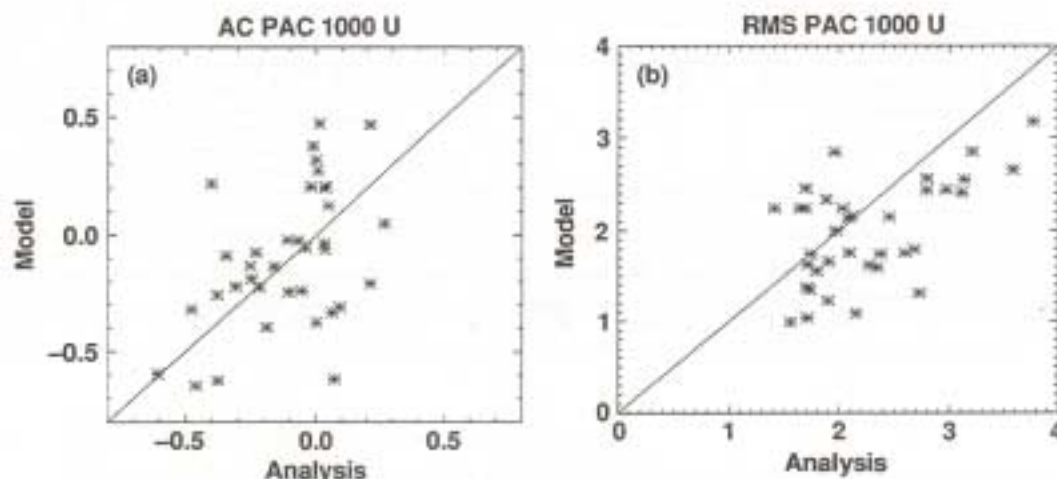

Fig. 13. (a) Anomaly correlation between all possible pairs of January monthly mean 1000 hPa zonal wind from 15S to 15N and 120E to 100W for the years 1980 to 1988 plotted as a scatter diagram. The values for the ECMWF analyses are plotted along the abscissa, model values along the ordinate. For the nine Januarys there are 36 pairs. (b) RMS between all possible pairs of January monthly mean 1000 hPa zonal wind from 15S to 15N and 120E to 100W for the years 1980 to 1988 plotted as a scatter diagram. The values for the ECMWF analyses are plotted along the abscissa, model values along the ordinate. For the nine Januarys there are 36 pairs.

coupled air–ocean system. Figures 11, 12, and 13 present data for this region and variable. Figure 11 shows an increase in the AC for nearly all time periods compared with the 200 hPa zonal wind. In addition, the periods of enhanced correlation tend to be more persistent than in Fig. 1, as was also the case for the 200 hPa winds.

In Fig. 13a the data have a linear correlation is 0.47. In Fig. 13b the RMS of the interannual variation between the model and the observations are comparable, with a tendency for the model to underestimate. This would indicate that SST plays a key role in modulating the variations of the 1000 hPa in the equatorial Pacific and that the model captures some of this interaction.

6.   Conclusions

The results presented above are in concert with those of Palmer(1987) who found a small extratropical response and a large tropical response to SST variability in a series of GCM experiments. The results presented are also consistent with the study of Newell and Xu (1992) on the correlations of atmospheric and ocean temperatures. The simple diagnostics used here do nothing to explain the nature of the forcing of the variability, nor do they permit insight into nature of the model's teleconnection patterns (such as the PNA) which have been documented for the atmosphere.

The conclusions which can be drawn from this preliminary study of low frequency variability are:

(1) There is a detectable low frequency signal in the modeled 500 hPa heights, corresponding to the 1982–83 and 1986–87 ENSO events. Outside of these times there is little relation between the monthly averaged SST and the midlatitude 500 hPa height.

(2) The simulated tropical 200 hPa and 1000 hPa zonal wind low frequency anomalies have a stronger relation to the ECMWF analyzed data than do the midlatitude heights. These results must be tempered with the evidence from the MSU data. The ECMWF analyses display a variability similar to that of the simulated data but both the analyses and the simulations are in only fair agreement with the MSU data. In the tropics the analyses and the simulation tend to agree more with each other than with the observations.

(3) The model tends to underestimate the interannual variability of the midlatitude 500 hPa heights, but overestimates the variability of the MSU temperatures as

compared to the analyses and MSU observations. This discrepancy might be due to poor simulation in the upper levels of the model. In the present model formulation there is no intention to accurately simulate the tropopause and lower stratosphere circulation.

(4) In the tropics the interannual variability of both the 200 hPa zonal wind and MSU temperature are underestimated by the model.

(5) The MSU data are a useful complement to the in situ data in evaluating the results of the comparison with the ECMWF analyses. This provides an important independent check upon the operational analyses.

A possible next step is to produce a simulation with a mean annual climatological SST pattern. Using this run as a control, one can than start to make estimates of the relative contributions of the intrinsic and externally forced variability to the low frequency interannual variations. In addition, more sophisticated diagnostic tools must be brought to bear to determine the nature of the tropical response to SST variations and the teleconnection patterns produced by the model. The results shown here provide encouragement to continue experimentation with the model.

REFERENCES

Gates, W. L., 1992: AMIP: The atmospheric model intercomparison project. *Bull. American Meteor. Soc.*, **73**, 1962–1970.

Hoerling, M. P., M. L. Blackmon and M. Ting, 1992: Simulating the atmospheric response to the 1985-87 El Niño cycle. *J. of Climate*, **5**, 669–682.

Hoskins, B. J., H. H. Hsu, I. N. James, M. Masutani, P. D. Sardeshmukh and G. H. White, 1989: Diagnostics of the global atmospheric circulation-based on ECMWF analyses 1979–1989. WRCP–27, WMO/TD–No. 326, Geneva, Switzerland, 217pp.

Hurrell, J. W. and K. E. Trenberth, 1992: An evaluation of monthly mean MSU and ECMWF global atmospheric temperatures for monitoring climate. (submitted to *J. Climate*).

Miller, M. J., A. C. M. Beljaars and T. N. Palmer, 1992: The sensitivity of the ECMWF model to the parameterization of evaporation from the Tropical oceans. *J. Climate*, **5**, 418–434.

Mo, K. and E. Kalnay, 1991: Impact of sea surface temperature anomalies on the skill of monthly forecasts. *Mon. Wea. Rev.*, **119**, 2771–2793.

Miyakoda, K., J. Sirutis and J. Ploshay, 1986: One month forecast experiments without anomaly boundary forcings. *Mon. Wea. Rev.*, **110**, 2363–2401.

Newell, R. E., and Z-X. Wu 1992: The interrelationship between temperature changes in free atmosphere and sea surface temperature changes. *J. Geophys. Res.*, **97(D4)**, 3693–3709.

Palmer, T. N., 1987: Modelling low frequency variability of the atmosphere. In: H. Cattle(Ed.) *Atmospheric and Oceanic Variability*, Royal Meteorological Society, Bracknell, 75–103.

Philander, S. G., 1990: *El Niño, La Niña, and the Southern Oscillation*, International Geophysics Series 46, Academic Press, New York, 293 pp.

Reynolds, R., 1988: A real time global sea surface temperature analysis., *J. Climate*, **1**, 75–86.

Spencer, R. W., and J. R. Christy, 1990: Precise monitoring of global temperature trends from satellites. *Science,* **247**, 1558–1562.

Spencer, R. W., and J. R. Christy, 1992: Precision and radiosonde validation of satellite gridpoint temperature anomalies, Part I: MSU channel 2. submitted to *J. Climate*.

Tibaldi, S., T. N. Palmer, C. Brankovic and U. Cubasch, 1991: Extended-range predictions with ECMWF models: Influence of horizontal resolution on systematic error and forecast skill. *Quart. J. Roy. Meteor. Soc.,* **116,** 835–866.

Wallace, J. M. and M. L. Blackmon, 1983: *Observations of low frequency atmospheric variability. Large-Scale Dynamical Processes in the Atmosphere.* B. J. Hoskins and R. P. Pearce (eds.), Academic Press, NY, 397 pp.